STRUCTURAL HEALTH MONITORING AT LOS ALAMOS NATIONAL LABORATORY

Charles R. Farrar and Scott W. Doebling
Los Alamos National Laboratory
Los Alamos, New Mexico, USA

Introduction

In the most general terms damage can be defined as changes introduced into a system that adversely effect its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state. This discussion is focused on the study of damage identification in structural and mechanical systems. Therefore, the definition of damage will be limited to changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely effect the current or future performance of that system.

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical and aerospace engineering communities. Current damage-detection methods are either visual or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiograph, eddy-current methods and thermal field methods. All of these experimental techniques require that the vicinity of the damage is known *a priori* and that the portion of the structure being inspected is readily accessible. Subjected to these limitations, such experimental methods can detect damage on or near the surface of the structure. The need for quantitative global damage detection methods that can be applied to complex structures has led to the development and continued research into methods that examine changes in the vibration characteristics of the structure.

The basic premise of vibration-based damage detection is that damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of that system. Although the basis for vibration-based damage detection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of structures that is normally measured during vibration tests. Stated another way, this fundamental challenge is similar to that in many engineering fields where the ability to capture the system response on widely varying length scales has proven difficult. Another fundamental challenge is that in many situations vibration-based damage detection must be performed in an *unsupervised learning* mode. Here, the term *unsupervised learning* implies that data from damaged systems are not available. These challenges are supplemented by many practical issues associated with making accurate and repeatable vibration measurements at a limited number of locations on complex structures often operating in adverse environments.

Los Alamos National Laboratory (LANL) has several ongoing programs to identify damage in structures and mechanical systems from changes in their dynamic characteristics. This paper provides a summary of LANL's involvement with this technology, past experiences in this field including damage detection studies on large civil engineering infrastructure and the directions that research in this area will be taking in the future. The research began by taking a strictly model-based approach to the vibration-based damage detection problem. Recent work has recognized that it is more appropriate to view the damage detection problem as an exercise in statistical pattern recognition. Therefore, a general statistical pattern recognition paradigm will be proposed. References are not list in this document. Instead, the reader is referred to the Los Alamos Damage Identification home page: http://ext.lanl.gov/projects/damage_id where all publications related to the studies discussed below can be downloaded.

Early Vibration-Based Damage Studies at Los Alamos

Vibration-based damage detection work at LANL had its beginnings almost 15 years ago when engineers in the Advanced Engineering Technology Group attempted to identify the onset of seismically-induced buckling in scale model nuclear reactor containments from changes in their measured vibration response. Other work included attempts to infer damage in seismically loaded scale-model reinforced concrete shear wall structures from changes in their vibration response.

Physicists in LANL's Condensed Matter and Thermal Physics Group developed and patented a damage ID system referred to as Resonant Ultrasound Spectroscopy (RUS) in the early 1990s. This system combined sine-sweep vibration testing with a homodyne detection system to make very precise measurements of small test specimen resonant frequencies. For objects of very regular geometry, such as ball bearings, this test system can provide accurate indications of material or geometric anomalies, such as ball bearing out-of-roundness. Subsequent applications of RUS include the detection of salmonella poisoning in eggs from changes in their vibration response, the screening of captured Gulf-War ammunition to determine if artillery shells contain conventional or chemical warheads, and the crack detection machined parts. Geophysicists at LANL are currently using RUS to identify damage in concrete and rocks.

Through collaboration with these physicists, engineers from the Engineering Analysis Group were asked to be a primary participant in the damage ID tests on the I-40 Bridge over the Rio Grande. The engineers from LANL performed the experimental modal analyses of the bridge in its undamaged and damaged conditions while engineers from Sandia National Laboratory ran a hydraulic shaker that provided the input for these vibration tests. The physicists contributed to these tests by demonstrating a non-contact vibration measurement system based on a microwave interferometer designed and constructed at LANL.

Participation on this project lead to two additional internally funded projects in LANL's Engineering Analysis Group related to vibration-based damage detection. Products resulting from these projects include an extensive review of the literature of vibration-based damage ID, a workshop held at LANL in September 1995, and a MATLAB-based computer code known as DIAMOND for statistical modal analysis, damage detection, and finite element model refinement.

Applications

Most of the work conducted at LANL in the area of vibration-based damage detection has focused on applications to civil engineering infrastructure. Analysis of data sets from modal tests of bridges has demonstrated the importance of quantifying the variability of the measured modal parameters resulting from environmental conditions. Statistical analysis techniques such as Monte Carlo simulation and Bootstrap analysis have played an important role in the quantification of such variability. Ongoing work is focused on the testing of idealized structures for the purposes of comparing the effectiveness and limitations of various damage ID techniques.

I-40 Bridge Study

To date, field verification of damage detection algorithms applied to large civil engineering structures are scarce as few full size structures are made available for such destructive testing. Because the I-40 bridges over the Rio Grande in Albuquerque, New Mexico were to be demolished and replaced, the investigators were able to introduce simulated cracks into the structure, perform vibration test before and after each level of damage had been introduced, and then use the test data to validate various damage ID methods. Damage detection algorithms were applied to these data and to numerical data from finite element simulations of the I-40 Bridge tests where other damage scenarios were investigated. Results from these investigations are some of the first comparative studies of various damage ID algorithms that have been reported in the technical literature.

Alamosa Canyon Bridge

The New Mexico State Highway and Transportation Department has designated the Alamosa Canyon Bridge in southern New Mexico as a bridge test facility. Numerous modal tests have been performed on this structure for the purposes of damage detection. With only limited abilities to introduce damage into this structure, recent tests have focused on quantifying the statistical variations in modal properties that result from changing environmental conditions. It is imperative that these changes are quantified and that changes resulting from damage are shown to be either greater than or different from those resulting from the test-to-test variations. Recent tests have been performed with the intent of comparing different statistical analysis procedures.

University of California, Irvine Bridge Piers

The University of California, Irvine (UCI) had a contract with CALTRANS to perform static, cyclic tests to failure on seismically retrofitted, reinforced-concrete bridge columns. With funds obtained through LANL’s University of California interaction office, staff from LANL’s Engineering Analysis Group were able to perform numerous experimental modal analyses on the columns. These modal tests were performed at stages during the static load cycle testing when various amounts of damage had been accumulated in the columns. These tests and the associated data obtained will be used to demonstrate a statistical pattern recognition process of vibration-based damage detection.

Eight Degree of Freedom Test System

When reviewing the literature, most damage detection studies examine either a beam or a complex structure such as an offshore platform. In an attempt to provide data from structures of intermediate complexity and still keep the fabrication cost reasonable, an eight degree-of-freedom, lumped-mass system was designed such that small quantifiable changes in stiffness or mass can be easily incorporated into the system. In addition, nonlinearities such as a crack opening and closing, variable frictional damping mechanisms, and rattling parts can also be simulated with this system. This system has been tested in a variety of configurations and results of these tests will be used for comparative studies of damage ID algorithms and finite element model updating methods.

Comparative Test Specimens

To provide data sets for comparative damage ID studies, a series of tests have been conducted on simple structures. The idea of these tests is to investigate a wide variety of structure types while keeping the cost of specimen fabrication low. These structures include an aluminum I-beam, an aluminum plate, a three-story "unistrut" frame structure, and a fifty-five gallon drum that is intended to simulate a shell structure. Linear and nonlinear damage was introduced incrementally in these structures and vibration data (both time-histories and frequency domain data) were measured for the undamaged and damaged structures. Various damage ID methods will be applied to these data sets for comparative studies. These data will be made available to other investigators for further study.

Rotating Machinery

To date, the most successful application of vibration-based damage detection technology has been for monitoring rotating machinery. The detection process is based on non-model based pattern recognition applied to time histories or spectra generally measured at a single point on the housing of the machinery during normal operating conditions. Often this pattern recognition is performed only in a qualitative manner. Databases have been developed that allow specific types of damage to be identified from particular features of the vibration signature. Typical damage that can be identified includes loose or damaged bearings, misaligned shafts, and chipped gear teeth. Currently, studies are being made of the rotating machinery applications to see if concepts used for damage detection in this class of systems can be adapted to defense systems. It is anticipated that a thorough review of the rotating machinery damage detection literature will be published with the next year.

Contributions

The investigators at LANL can point to three primary successes resulting from these investigations of vibration-base damage detection. First, the literature review that was published is, in the authors' opinion, the most comprehensive summary of the literature in this field to date. Second, the computer code DIAMOND is to the authors' knowledge the only code that assembles many of the recent advances in vibration-based damage detection algorithms into one graphical user interface code. This code has recently been made available to the public and can be download from http://ext.lanl.gov/projects/damage_id. In addition, sample data sets such as those from the I-40 Bridge tests can be downloaded at this same site and used for comparative purposes. The final success of these projects relates to the fact that funding has been made available to work on defense system applications.

Where Are We Going From Here?

Current work is focusing more on incorporating the statistical pattern recognition technology and machine learning into the damage detection process. The damage detection process can be divided into four segments: 1.) Definition of damage and operational evaluation; 2.) Data acquisition and cleansing; 3.) Feature extraction and data compression; and 4.) Statistical model building.

First, damage must be defined for the system being investigated. Next, operational evaluation is performed. This process begins to set the limitations on the monitoring. The evaluation starts to tailor the health monitoring process to features that are unique to the monitored system and tries to take advantage of unique features of the postulated damage. The data acquisition portion of the structural health monitoring process involves selecting the types of sensors to be used, selecting the location where the sensors should be placed, determining the number of sensors to be used, and defining the data acquisition/storage/transmittal hardware. Also, as data is acquired decisions must be made regarding its quality and if it should be used in the feature extraction process. This process of selectively accepting or rejecting the data is referred to as data cleansing. Identification of data features used to distinguish the damaged structures from undamaged ones receives the most attention in the technical literature. Inherent in this process is the compression of data. Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as *supervised learning*. *Group classification* and *regression analysis* are supervised learning algorithms. *Unsupervised learning* refers to algorithms that are applied to data not containing examples from the damaged structure and focuses on multi-variate density estimate and the identification of outliers.

This technology is currently being applied to defense system damage detection studies. Also, Los Alamos is about to enter into a cooperative research agreement with private industry to develop commercial technology for vibration-based monitoring of civil engineering infrastructure.

Acknowledgments

The authors thank the following people whose work is summarized in this paper: Bill Baker, Phil Cornwell, Tim Darling, Tom Duffey, Norm Hunter, Paul Johnson and Albert Migliori. Also, the students, and collaborators that have worked on these projects deserve tremendous credit.